A TWO-DIMENSIONAL IMAGING WALKWAY FOR GAIT ANALYSIS

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Abstract: This paper describes basic work on a new approach to implementing a clinical walkway for imaging foot placement with high resolution in two dimensions and in time over several steps, utilizing a relatively inexpensive technology. It uses a novel principle for sensing and data gathering through an array of magnetostrictive delay lines made of amorphous magnetic alloy.

Imaging has been demonstrated and a prototype system is currently under construction. Foot-ground contact images are read by a computer in real time. Software has been developed for rapid analysis and presentation of spatial and temporal gait parameters, based on two-dimensional foot placement. The sensing array is simple and robust and it should be possible for reliable systems to be built at a low enough cost to be widely used in the clinical environment with minimal technical support. Progress has also been made towards achieving proportional pressure mapping by means of a similar structure. The system might also find applications in contexts such as comfort of seating, wheelchairs and artificial limbs, and in ergonomics and sport.

Introduction

Defects in gait arise from many disorders and precise methods of data capture and analysis are needed to enable suitable treatment to be brought to bear at an early stage, and to allow progress under treatment to be accurately monitored. Walkways have a well-established place in gait analysis and many types have been developed [1,2,3,4,5,6,7], but there is still much room for improvement in terms of the quality and quantity of clinical information obtained. For instance, many past systems have tended to concentrate on resolving the gait pattern only in the direction of walking. A scheme is presented here for a clinical walkway which is intended to achieve high-resolution imaging of foot placement in two dimensions, with high time resolution, over several steps and with a relatively inexpensive technology. The design is based on an original approach to the problem of sensing foot-to-ground contact and data gathering by means of magnetostrictive delay lines which is derived from a concept originally developed for memory storage in early computers [8,9] and now widely used in graphic digitisers.

Sensor array

In a basic embodiment of the idea there is a delay line consisting of a wire or ribbon of a material having high magnetostriction, and there is a conductor placed orthogonally nearby which carries a pulsed current. The resulting magnetic field causes an acoustic pulse to be launched in the delay line at the point of crossing, travelling in both directions. The acoustic signal can be sensed elsewhere on the line by a coil of a few hundred turns by means of the inverse magnetostrictive effect. In practice the speed of propagation is about 5 mm per microsecond and duration of the excitation pulse is about 2 microseconds.
The arrangement used here is an adaptation of the above and depends on a balanced conductor/delay line structure as shown in Fig 1. A pair of conductors arranged symmetrically above and below the delay line carry equal pulsed currents in the same direction. These have opposing effects on the delay line, so that the net acoustic pulse has (ideally) zero amplitude. However, when the symmetry is altered by bringing a highly permeable body close to the crossing, a pulse is generated. Such a crossing thus becomes a sensing point for the proximity of a permeable body. The wires must be very closely spaced in order to achieve high and very localised sensitivity, and current pulses are of several amps. Fig 1 also shows how simultaneous excitation is arranged at multiple crossings so as to produce a train of pulses which can be identified with the points of origin by their time of arrival at the detector. The diagram shows a permeable body in the vicinity of only one crossing and the photograph Fig 1b shows the corresponding output waveform, while Fig 1c shows the effect when a similar body is placed at the other crossing.

To form a 2-dimensional grid, multiple exciting conductors are used; there are also multiple delay lines, all excited by the same set of conductors. This is the structure which is incorporated into the floor. This sharing of circuits, and the serialisation of the data, are major attractions of the approach, in that a numerically large array of sensing points is achieved with a very simple structure and minimal hardware.

The foot is made detectable by incorporating a layer of permeable material into the sole of the shoe, so that during a placement all points on which the material rests produce
large pulses. At present only a binary condition is sensed, by detecting pulse amplitude in relation to a fixed threshold. The pulse trains are read by a computer which can reconstruct and then display the areas of contact in real time.

In practical form the detector array consists of a sandwich of epoxy-glass laminates as used in multilayer printed circuit boards, less than 0.5 mm thick overall, which rests on a rigid, insulating supporting surface (Fig 2). The outer layers carry an array of etched copper conductors in the X direction while the inner layer is machined to form channels which house the delay lines in the Y direction. There is thus formed a 5 mm x 5 mm grid of sensing points.

Construction of the floor is very simple and a large, precision assembly can be made economically. Full size panels will be 32 cm x 64 cm; these will be built into modular floor units which will be laid side by side to form a seamless continuous detector 64 cm wide, with the delay lines running across the direction of walking. It is planned initially to build a walkway 64 cm wide by about 2.5 metres long.

Delay lines

The delay lines are ribbons of Metglas 2605SC amorphous alloy, about 0.8 mm wide and 0.03 mm thick. These must be accommodated loosely without pinching, and this complicates construction. It is the combination of very high permeability and high magnetostriction which determines choice of this material, and perhaps even makes the whole concept viable. But while amorphous ribbon is attractive on account of its sensitivity, its characteristics as a delay line are not very satisfactory, as it exhibits marked non-uniformity of amplitude response along its length [10]; this is one of the main reasons for adopting the balanced structure for the exciting conductors.

The ends of the delay line have to be terminated so that acoustic reflections die away.
quickly, by means of a suitable coating over a length of a few centimetres, in order to allow a high interrogation rate. A reflection of less than 2% in amplitude can be achieved fairly easily and this allows a repetition cycle time of less than 1 msec with 1-metre delay lines. A further limiting factor is the dynamic response to the excitation current which effectively sets a lower limit to the duration of output pulses, so that pulses due to simultaneous excitation at two points will overlap if the points are closer than about 50 mm. This is overcome by arranging the conductors in 16 interleaved sets which are excited in sequence via a demultiplexer, to achieve 5 mm resolution. Thus, taking both factors into account, it takes about 16 msec to derive all the data from a line of 1 metre overall length.

Attenuation with distance is also significant, and we have observed that signal amplitude decays by about 60% per metre even in suitably treated ribbons. This will probably be acceptable for binary images, but if necessary it can be compensated by simple circuit arrangements. An associated characteristic of the material in ribbon form is a significant amount of scattering, which distorts the signal and reduces spatial resolution. However, there are signs that markedly better performance in these respects, as well as much better uniformity, may be achievable with amorphous wires that are now becoming available [11]. Another consequence of using these materials is that because of the very high permeability attention has to be paid to ambient magnetic fields.

At present there is some practical inconvenience in the manufacture of delay lines. To suit the 5 mm pitch, they have to be no wider than about 1 mm. Ribbons of this width do not appear to be readily available commercially and a method has therefore been developed for producing them from 50 mm wide ribbons by etching. The process is fairly time-consuming and great care is required to produce usable delay lines, but recently we have had successful results with 1 mm ribbons cast to order at the University of Hull.

Circuitry

Fig 3 gives a functional outline of the present system. Along one edge of the walkway circuit boards carry the front-end electronics for the delay lines. Each ribbon passes through a detector coil which has associated with it an amplifier and comparator to produce logic-level pulses. These are quite simple circuits built in surface mount technology and are located at 5 mm intervals to correspond with the lines.

Comparator outputs are grouped in adjacent eights and these are accessed via a multiplexing bus which directs them to a 64-bit wide buffer memory. The bus is arranged so that at any one time the addressing logic controlled by the computer connects 64 adjacent signals, from a contiguous 32-cm length along the walking direction, to the buffer. The location of this window can be adjusted in steps of 4 cm, within microseconds, in order to scan active areas. Additional logic is planned for detecting new heelstrikes without the need for a software search. One complete excitation cycle loads the buffer with an image of the full width of the windowed part of the walkway, with one bit per grid point. A software cycle then transfers the contents to main computer memory. The addressing logic takes care of the rearrangement needed to compensate for interleaved excitation without a time penalty.
A version of the interface logic is now being implemented in Xilinx reprogrammable logic cell arrays. We see the flexibility and speed of redesign afforded by this approach as likely to be valuable as we anticipate the need to make major changes and extensions to the circuitry.

**Software**

The intention is to develop a complete instrument around the sensor array, which in addition to the computer and hardware interface also embraces software for processing and for a user-friendly interface to the clinician. The software is mainly mouse- and menu-driven and provision is made for an image of the whole walkway to be displayed on screen. Software has been developed concurrently, mostly with simulated data. The system is based on the Acorn Archimedes computer which offers high speed, good graphics handling and ease of interfacing to hardware. Work is also in hand to develop versions of the hardware and software for the IBM Personal Computer.

Each frame might be thought of as an image of the whole walkway, but because of the binary and very localised nature of footprint images only a very small amount of data need be transferred for updating. An upper estimate of the data required to record a single foot contact may be based on a boundary rectangle of 300 mm x 100 mm, ie 60 x 20 points, which corresponds to 150 bytes if no compression is used, with a few additional bytes to record position. Thus a useful sampling rate of 20 frames per second requires a net rate of transfer into the computer of only 3000 bytes per second. For storage this might be compressed to about 1000 bytes per second of recorded data.
With a single-frame buffer, frame rate is also limited by software and by the hardware port. A typical figure observed is that one frame can be acquired in about 10 msec, which is comparable with the rate at which the sensor array can be cycled. This rate could be considerably improved, mainly by providing direct access to main memory space. Maintaining a real-time screen display takes about 10 times this figure.

Processing and display software is written in a combination of C and, where appropriate, machine code. Successive frames for one pass of the subject are stored at sequential locations in memory and the whole is the primary data for processing. The several successive images which correspond to a single foot contact are merged to form a composite foot outline, and this is the basis from which foot position and orientation are calculated. Standard spatial gait measures such as step and stride lengths, step width and toe out angles are calculated from a sequence of these placements, and displayed. Detection of heel strike and toe off are derived from inspection of successive frames, and from these other temporal parameters are displayed.

One method which we have used to define position is to calculate the centroid of the composite footprint; this takes about 1 second in machine code. Similarly the centroid of the contact area for each stance frame is calculated and its position plotted in relation to the image so that its progress through stance can be displayed, and if necessary replayed at slow speed. Currently a simpler approach is being considered in which, instead of an overall covering, the foot marker is a smaller longitudinal magnetic strip fitted in known relation to the foot, which would require less data transfer and processing to establish placement.

Conclusion

This is an early report; a new principle has been found to show considerable promise but we have yet to explore the clinical potential of the system. The prospect is for an accurate imaging system covering several gait cycles with a resolution of 5 mm x 5 mm, suitable for children's feet, with an array of typically 512 x 128 sensors. While the essential features have been proved and small images demonstrated, much remains to be done to establish performance ratings and implement known possibilities for improvement.

At this stage attention is being concentrated on a system which captures foot contact area only, and there is much scope for development based on this capability. However, the long term aim is to progress to a version which responds proportionally to foot/ground pressure with the same spatial resolution. Results of experiments towards this end have been very promising, with a new type of magnetostrictive sensor which is interrogated by the same form of delay line array [12]. A characteristic of many walkways is the high compliance of the walking surface which among other things causes apparent spread of the detected contact area. This was one of the factors which led to our present design in which the walking surface is totally rigid. Furthermore, the proposed scheme for proportional detection would appear to offer the same benefit.

Future developments might include an in-shoe version of the device. This could make it
possible to employ a self-contained portable system without trailing wires, for long-term monitoring in the normal environment, outdoors, on slopes, etc., thus avoiding psychological effects which can distort observations made in the clinic. Other medical contexts in which variants of the technique might be applied include measurement of stress distribution in investigating the comfort of seating and artificial limbs, and there are possible applications in tactile devices such as robotic grippers.

The clinical community has a clear need for inexpensive gait instrumentation, especially with regard to the increasing elderly population, and the literature reveals much effort in this direction. Gait laboratories which gather a comprehensive range of data are becoming more common, and in this context a high-resolution pressure-sensitive walkway is complementary to methods such as video capture, EMG recording and goniometry. Attention is also being given to the development of expert systems software and its application to diagnosis and decision support in this area [13]. The effectiveness of this approach should be greatly enhanced by direct access to the information which such a walkway would provide.

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References